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(Superseding IS 5728)
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Indian Standard

CALCULATION OF THE EFFECTS OF SHORT-CIRCUIT CURRENTS

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Indian Standard

CALCULATION OF THE EFFECTS OF SHORT-CIRCUIT CURRENTS

NATIONAL FOREWORD

This Indian Standard which is identical with IEC Pub 865 (1986) 'Calculation of the effects of short-circuit currents', issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendations of the Electrical Installations Sectional Committee (ET 20) and approval of the Electrotechnical Division Council.

An important criterion for the proper selection of a circuit-breaker or any other fault protective devices for use at a point in an electrical circuit is the information on maximum fault current likely at that point. The electromagnetic, mechanical and thermal stresses which a switchgear and the associated apparatus have to withstand depends on the fault current. Proper selection of breaking and withstand capacities play a major role in the health of the electrical installations. Realizing this need and to provide uniform guide for calculation of short-circuit currents, IS 5728 was brought out in 1970.

Subsequent to the preparation of this standard, considerable information has been collated the world over on calculation of fault levels under different and specific circumstances. There was also a need to simplify calculation techniques in practical way commensurate with the modern arithmetic tools available to engineers in the form of computers, digital transient network analysers etc. With an objective to establish a general, practicable and concise procedure for short-circuit current calculations IS 5728 has been taken up for revision, aligning its contents with IEC 865 (1986).

This Indian Standard supplements the provisions of IS 13234 : 1991/IEC 909 (1988) by covering standardized procedures for the calculation of the electromagnetic and thermal effects of fault currents in electrical circuits.

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1. Scope

This standard contains standardized procedures for the calculation of the effects of the short-circuit currents in two sections as follows:

Section One — The electromagnetic effect on rigid conductors and slack conductors.

Section Two — The thermal effect on bare conductors.

Only a.c. systems for rated voltages up to and including 72.5 kV are dealt with in this standard.

2. Symbols

The symbols used in this standard and the quantities which they represent are given in the following lists:

2.1 *Symbols for Section One – Electromagnetic effects*

A	Conductor cross-section	mm^2
a	Centre-line distance between conductors	m
a_s	Effective conductor central distance, see Table I	m
a_{1s}	Centre-line distance between conductors	m
b	Dimension of the sub-conductor perpendicular to the direction of the force	m
c	Factor for the influence of spacers or stiffening elements, see Figure 3, page 29	
d	Dimension of the sub-conductor in the direction of the force	m
E	Young's modulus	N/mm^2
F	Force acting between two parallel long conductors during a short-circuit	N
F_d	Force on support of rigid conductors during a short-circuit (peak value)	N
F_f	Tension in a flexible conductor after a short-circuit	N
F_m	Force between main conductors	N
F_{m2}	Force between main conductors during a line-to-line short-circuit	N
F_{m3}	Force acting on central main conductor during a balanced three-phase short-circuit	N
F_s	Force between sub-conductors	N
F_{st}	Static tension in a flexible conductor	N
F_t	Tension in a flexible conductor during a short-circuit	N
F'_o	Force per unit length on outer phase flexible conductor caused by a short-circuit current	N/m
f	System frequency	Hz
f_c	Natural frequency of a main conductor	Hz
f_o	Basic frequency	Hz
g_n	Conventional value of acceleration of gravity	m/s^2
I_{k3}	Three-phase symmetrical short-circuit current (r.m.s.)	kA
i_p	Peak short-circuit current	kA
i_{p2}	Peak short-circuit current in case of a line-to-line short-circuit	kA
i_{p3}	Peak short-circuit current in case of a balanced three-phase short-circuit	kA
i_1, i_2	Instantaneous values of the currents in the conductors	kA
J	Second moment of conductor area	cm^4
J_s	Second moment of sub-conductor area	cm^4
k	Number of spacers or stiffening elements, see Figure 3	
k_{1s}	Factor for effective conductor central distance, see Figure 1, page 28	
l	Distance between supports	m
l_s	Distance between spacers or stiffening elements	m
m'	Main conductor mass per unit length	kg/m
m'_s	Mass of sub-conductor per unit length	kg/m
m_z	Total mass of one stiffening element or spacer between supports	kg
n	Number of sub-conductors	
q	Factor of plasticity, see Table III	
$R_{p0.2}$	Yield point	N/mm^2
S	Resultant spring constant of conductor dead end	N/mm
t_u	Dead-time of three-phase auto-reclosure	s
V_F	Ratio between dynamic and static force on support, see Figure 4, page 30	

V_r	Ratio between stress with and without unsuccessful three-phase auto-reclosure, see Figure 5, page 30	
V_σ	Ratio between dynamic and static conductor stress, see Figure 4, page 30	
$V_{\sigma s}$	Ratio between dynamic and static sub-conductor stress, see Figure 4	
Z	Section modulus	cm^3
Z_s	Section modulus for sub-conductor	cm^3
α	Factor for force on support, see Table II	
β	Factor for main conductor stress, see Table II	
γ	Factor for natural frequency estimation, see Table II	
κ	Factor for peak short-circuit current	
ζ, φ, ψ	Factors for tensile force in flexible conductor, see Figure 6, page 31	
σ_m	Bending stress in main conductor	N/mm^2
σ_s	Bending stress in sub-conductor	N/mm^2
σ_{tot}	Resulting conductor stress	N/mm^2

2.2 *Symbols for Section Two – Thermal effects*

I_k	Steady state short-circuit current (r.m.s.)	kA
I_k''	Initial symmetrical short-circuit current (r.m.s.)	kA
I_{th}	Thermal equivalent short-circuit current (r.m.s.)	kA
I_{thi}	Individual thermal equivalent short-circuit current at repeated short-circuits (r.m.s.)	kA
I_{thr}	Rated short-time current (r.m.s.)	kA
m	Factor for the heat effect of the d.c. component, see Figure 7*a)*, page 32	
n	Factor for the heat effect of the a.c. component, see Figure 7*b)*, page 32	
S_{th}	Thermal equivalent short-circuit current density (r.m.s.)	A/mm^2
S_{thr}	Rated short-time current density (r.m.s.) for 1 s	A/mm^2
T_k	Short-circuit duration	s
T_{ki}	Individual short-circuit duration at repeated short-circuits	s
T_{kr}	Rated short-time	s
θ_b	Conductor temperature at the beginning of a short-circuit	°C
θ_e	Conductor temperature at the end of a short-circuit	°C

3. General definitions

3.1 *Main conductor*

A conductor or a composed arrangement of a number of conductors carrying the total current in one phase.

3.2 *Sub-conductor*

A conductor which carries a certain part of the total current in one phase and is a part of the main conductor.

3.3 *Support*

An insulating device between a live conductor and the earthed structure or between main conductors.

Note. — Under action of electromagnetic forces, in the given position, the support might be exposed to bending, tension and/or compression due to electromagnetic forces between the conductors.

3.4 *Fixed support*

A support of a conductor which does not permit the conductor to move angularly at the supported point.

3.5 *Simple support*

A support which permits angular movement of the conductor.

3.6 *Spacer*

A mechanical element between conductors which, at the point of installation, prevents sub-conductors being displaced towards each other.

3.7 *Stiffening element*

A special spacer intended to prevent any movement between rigid sub-conductors at its place.

3.8 *Rated short-time current*

The r.m.s. current which the electrical equipment is able to withstand during the rated short-time under specified conditions.

Notes 1. — It is possible to state several pairs of values of rated short-time current and short-time; for thermal effect 1 s is used in most IEC specifications.

2. — The rated short-time current as well as the corresponding short-time are stated by the manufacturer of the equipment.

3.9 *Rated short-time current density and rated short-time for conductors*

The r.m.s. value of the current density which a conductor is able to withstand for the rated short time.

Note. — The rated short-time current density is determined according to Clause 10.

3.10 *Thermal equivalent short-circuit current*

A constant r.m.s. value of current having the same thermal effect and the same duration as the actual short-circuit current, which may comprise d.c. component and may subside in time.

Note. — If repeated short-circuits occur (i.e. repeated reclosures) a resulting thermal equivalent short-circuit current is evaluated (see Sub-clause 10.2).

3.11 *Thermal equivalent short-circuit current density*

The ratio of the thermal equivalent short-time current and the cross-section area of the conductor.

3.12 *Duration of short-circuit current*

The time interval between the initiation of the short-circuit and the final breaking of the current in all phases by the circuit-breakers or fuses.

Note. — The time interval in which the current does not flow need not be considered.

SECTION ONE — THE ELECTROMAGNETIC EFFECT ON RIGID CONDUCTORS AND SLACK CONDUCTORS

4. **General**

With the calculation methods presented in this section, forces on insulators, stresses in rigid conductors and tensile forces in slack conductors can be estimated.

5. **Mechanical forces due to short-circuit currents**

5.1 *General*

Currents in parallel conductors will induce electromagnetic forces between the conductors. When the parallel conductors are long compared to the distance between them, the forces will act evenly distributed along the conductors.

When the currents are in opposite directions the electromagnetic force is a repulsion which tends to induce deformations that would increase inductance of the circuit.

The value of the force in a given direction can be calculated by considering the work done in the case of a virtual displacement in the actual direction. As the work is done by the electromagnetic force, it must be equal to the change in the energy in the magnetic field caused by this virtual displacement. This leads to the following equation for the force F_x in direction x:

$$F_x = \frac{1}{2} i^2 \frac{dL}{dx} \tag{1}$$

where L is the self-inductance of the circuit and i the instantaneous value of the current.

For simple and idealized configurations, formulae for the calculation of inductance are available. However, in most cases approximations are necessary to give practical calculation methods.

The force between two conductors is proportional to the square of the current, or to the product of the two currents. As the current is a function of time, the force will also be a function of time. In the case of a short-circuit current without a d.c. component the force will vary with twice the frequency of the current. A d.c. component in the short-circuit current will give rise to an increase of the peak value of the force and to a component of force varying with the same frequency as the current. The peak value of the force is of particular interest in the case of mechanically rigid structures.

The force will result in bending stress on rigid conductors, tension stress and deflection in flexible conductors and bending, compression or tension loads on the supports.

5.2 *Calculation of forces*

The calculation method in this section is based on the general equation (1), neglecting the variations in distance during the short-circuit.

5.2.1 *Forces between two parallel conductors*

The forces in newtons acting between two long parallel conductors are given by the formula:

$$F = 0.2\, i_1\, i_2 \frac{l}{a} \quad \text{N} \tag{2}$$

where l is the distance, in metres, between supports, i_1 and i_2 are the instantaneous values of the currents in the conductors in kiloamperes, a is the centre-line distance between the conductors in metres.

When the currents in the two conductors have the same direction, the forces are attractive. When the direction of the currents is opposite, the forces are repulsive.

5.2.2 *Calculation of peak force between the main conductors during a three-phase short-circuit*

In a three-phase system with the conductors arranged at the same intervals on the same plane, the maximum force acts on the central conductor during a three-phase short-circuit and is:

$$F_{m3} = 0.2\, i_{p3}^2 \frac{l}{a_s}\, 0.87 \quad \text{N} \tag{3}$$

where i_{p3} in kiloamperes is the peak value of the a.c. component of the short-circuit current in the case of a balanced three-phase short-circuit.

Note. — Formula (3) can also be used for calculating the resulting peak force when the conductors are in the corners of an equilateral triangle and where a_s is the length of the side of the triangle.

5.2.3 *Calculation of peak force between the main conductors during a two-phase short-circuit*

The maximum force acting between the conductors carrying the short-circuit current during a two-phase short-circuit is:

$$F_{m2} = 0.2\, i_{p2}^2 \frac{l}{a_s} \quad \text{N} \tag{4}$$

where i_{p2} in kiloamperes is the peak short-circuit current in the case of a line-to-line short-circuit.

5.2.4 *Calculation of peak value of forces between rigid sub-conductors*

The maximum force acts on the outer sub-conductors and is between two spacers:

$$F_s = 0.2 \left(\frac{i_p}{n}\right)^2 \frac{l_s}{a_s} \text{ N} \tag{5}$$

when the short-circuit current is evenly distributed between the sub-conductors; n is the number of sub-conductors, l_s is the distance between spacers or stiffening elements, in metres, and a_s is the effective distance between sub-conductors, in metres.

5.2.5 *Effective distance between conductors and sub-conductors*

The forces between current-carrying conductors are dependent on the geometrical configuration and the profile of the conductors. For this reason a_s has been introduced in Sub-clauses 5.2.2, 5.2.3 and 5.2.4. However, if the dimensions of the cross-sections of the conductors are smaller than the distance between the conductor centres, in Sub-clauses 5.2.2 and 5.2.3 a_s may be replaced by a.

Some values for a_s are given in Table I. For other distances and conductor dimensions the formula

$$\frac{1}{a_s} = \frac{k_{12}}{a_{12}} + \frac{k_{13}}{a_{13}} + \frac{k_{14}}{a_{14}} + \ldots + \frac{k_{1n}}{a_{1n}} \tag{6}$$

can be used

The values for $k_{12}, \ldots, k_{1n}$ are to be taken from Figure 1, page 28.

Note. — The forces due to bends and the influence of a large amount of magnetic material close to the conductors are usually of low importance. For the calculations, see existing publications.

6. Calculation of stresses in rigid conductors and forces on supports

6.1 *General*

The conductors may be supported in different manners, either fixed or simple or in a combination of both, and may have two, three, four or several supports. Depending on the kind of support and the number of supports, the stress in the conductors and the forces on the supports will be different for the same short-circuit current. The formulas given also take the elasticity of the supports into account.

The stresses in the conductors and the forces on supports also depend on the ratio between the natural frequency of the mechanical system and the frequency of the electromagnetic force. Especially in the case of resonance, or near to resonance, the stresses and forces in the system may be amplified.

6.2 *Calculation of stresses in rigid conductors*

The assumption that the conductor is rigid means that the axial forces are disregarded. Under this assumption the forces acting are bending forces and the general formula for the bending stress in the supported main conductor is:

$$\sigma_m = V_\sigma V_r \beta \frac{F_m l}{8 Z} \text{ N/mm}^2 \tag{7}$$

where for F_m either the value F_{m3} (three-phase short-circuit) or F_{m2} (line-to-line short-circuit) is to be used.

The bending stress in a sub-conductor is:

$$\sigma_s = V_{\sigma s} V_r \frac{F_s l_s}{16 Z_s} \text{ N/mm}^2 \tag{8}$$

where Z and Z_s are section moduli, V_σ, $V_{\sigma s}$ and V_r are factors taking into account the dynamic phenomena and β is a correction factor depending on the type of supports, fixed or simple, and the number of supports.

The factor β is to be taken from Table II and V_σ, $V_{\sigma s}$ and V_r from Figures 4 and 5, page 30.

The maximum possible values are $V_\sigma = V_{\sigma s} = 1$.

In the case of three-phase auto-reclosure, the factor $V_r = 1.8$ is to be applied, otherwise $V_r = 1$.

For further consideration see Sub-clause 6.4.

6.2.1 *Permitted conductor stress*

A single conductor is assumed to withstand the short-circuit forces when:

$$\sigma_m \leq q\, R_{p0.2} \qquad (9)$$

where $R_{p0.2}$ is the stress corresponding to the yield point.

The factor q is to be taken from Table III.

When a main conductor consists of two or more sub-conductors the total stress in the conductor is:

$$\sigma_{tot} = \sigma_m + \sigma_s \qquad (10)$$

Note. — σ_{tot} is the algebraic sum of σ_m and σ_s independent of the loading directions (see Figure 2, page 28), but the location is to be considered.

The conductor is assumed to withstand the short-circuit forces when:

$$\sigma_{tot} \leq q\, R_{p0.2} \qquad (11)$$

It is necessary to verify that the short-circuit does not affect the distance between sub-conductors too much, otherwise a value

$$\sigma_s \leq R_{p0.2} \qquad (12)$$

is recommended.

In Table III the highest acceptable values for q for different cross-sections are given. For $q > 1.0$ small permanent deformations may occur (approximately 1% of the distance between supports for q-values according to Table III) which do not jeopardize the safety of operation.

Note. — For the yield point of conductor materials, $R_{p0.2}$, the standards often state ranges with minimum and maximum values. If only such limit values rather than actual readings are available, the minimum value should be used in Sub-clause 6.2.1 and the maximum value in Sub-clause 6.3.

6.2.2 *Section modulus of main conductors composed of sub-conductors with rectangular cross-section*

The bending stress and consequently the mechanical withstand of the conductor depend on the section modulus.

If the stress occurs in accordance with Figure 2*a)*, page 28, the section modulus Z is equal to the sum of the section moduli Z_s of the sub-conductors (Z_s with respect to the axis x-x).

If the stress occurs in accordance with Figure 2*b)* and in the case there is only one or no stiffening element within a supported distance the section modulus Z is equal to the sum of the section moduli Z_s of the sub-conductors (Z_s with respect to the axis y-y).

When within a supported distance there are two or more stiffening elements, higher values may be used. For main conductors composed of sub-conductors of rectangular cross-section with a space between the bars equal to the bar thickness, 60% of the section modulus with respect to the axis *0-0* may be used. For conductor groups having profile cross-section, approximately 50% of the section modulus with respect to the axis *0-0* may be used. See Table IV.

6.3 *Calculation of forces on supports of rigid conductors*

The dynamic force F_d is to be calculated from:

$$F_d = V_F\, V_r\, \alpha\, F_m \qquad (13)$$

where for F_m either the value F_{m3} or F_{m2} is to be used.

The maximum possible values of $V_F \cdot V_r$ can be estimated as follows:

$$V_r \cdot V_F = 1 \qquad \text{when } \sigma_m + \sigma_s \geqslant 0.8\ R_{p0.2}$$

$$V_r \cdot V_F = \frac{0.8\ R_{p0.2}}{\sigma_m + \sigma_s} \qquad \text{when } \sigma_m + \sigma_s \leqslant 0.8\ R_{p0.2}$$

The value of $V_F \cdot V_r$ is not higher than 2.7 for a three-phase short-circuit, and 2.0 for a two-phase short-circuit.

For further consideration see Sub-clause 6.4.

The factor α is dependent on the kind and the number of supports and is to be taken from Table II. See Note 2 to Table II. Regarding permitted load on insulator, see Clause 8.

6.4 *Calculation with special regard to conductor oscillation*

The formulae in Sub-clauses 6.2 and 6.3 give bending stresses and forces on supports achieved from a calculation of a load which is assumed static. In Sub-clauses 6.2 and 6.3 three factors, V_σ, V_F and V_r are introduced to take into account the natural frequency of the conductor. Some figures are also given for V_σ, V_F and V_r which give the highest possible stresses and forces.

6.4.1 *Calculation of relevant natural frequency*

The relevant natural frequency of a single conductor can be calculated from:

$$f_c = \frac{\gamma}{l^2} \sqrt{\frac{E\,J}{m'}} \quad \text{Hz} \qquad (14)$$

The factor γ is dependent on the kind and number of supports and is given in Table II.

For a main conductor composed of sub-conductors, J and m' must apply to the main conductor design. If the sub-conductors are of rectangular cross-section the relevant natural frequency of the main conductor can also be calculated as:

$$f_c = c f_o \qquad (15)$$

where:

$$f_o = \frac{\gamma}{l^2} \sqrt{\frac{E\,J_s}{m'_s}} \quad \text{Hz} \qquad (16)$$

The factor c is to be taken from graph *a)* or *b)* of Figure 3, page 29. In the case of no stiffening elements $c = 1$.

For the calculation of sub-conductor stress, taking the relevant natural frequency into account, the formula (14) is to be used. In this case replace l by l_s, m' by m'_s and J by J_s and use $\gamma = 0.356$.

Note. — The second moments J and J_s are calculated according to Figures 2*a)* or 2*b)*, page 28.

6.4.2 *The factors V_F, V_σ, $V_{\sigma s}$ and V_r*

The factors V_F, V_σ, $V_{\sigma s}$ and V_r as functions of the ratio f_c/f, where f is the system frequency in hertz, are a little different if a two-phase short-circuit is concerned and they are also dependent on the mechanical damping of the conductor system. For practical calculations these factors can be taken from Figure 4, page 30, for a multi-phase system. Excepted are structures with small relevant natural frequencies of conductor $f_c/f < 0.5$, where $\kappa < 1.6$; for these structures $V_F = V_\sigma = V_{\sigma s} = 1$ is to be applied.

For three-phase auto-reclosure the factor V_r can be taken from Figure 5, page 30; in other cases $V_r = 1$.

7. Calculation of tensile forces in slack conductors (line conductors)

A short-circuit current in a slack conductor will cause a tensile force in the conductor which will affect insulators, support structures and apparatus. It is necessary to distinguish between the tensile force F_t during the short-circuit (described in Sub-clause 7.1) and the tensile force F_f after the short-circuit, when the conductor falls back to its initial position (described in Sub-clause 7.2). To determine the dynamic stress of the supports, the higher value F_t or F_f is to be used.

Note. — For span lengths exceeding 20 m the use of the following formulae is not recommended.

7.1 *Tensile force F_t during the short-circuit*

The force F_t is calculated with:

$$F_t = F_{st}(1 + \varphi\psi) \quad \text{N} \qquad (17)$$

where F_{st} is the static tension in the conductor

$$\varphi = 3\left[\sqrt{1 + \left(\frac{F'_0}{g_n\, m'}\right)^2} - 1\right] \qquad (18)$$

where $g_n\, m'$ is the mass of the conductor per metre.

F'_0 is the force per metre in the outer phase conductor produced by the short-circuit current and calculated according to

$$F'_0 = 0.15\ \frac{I_{k3}^2}{a} \quad \text{N/m} \qquad (19)$$

where I_{k3} is the three-phase short-circuit current in kiloamperes (r.m.s.) and a, in metres, the centre-line distance between conductors.

The factor ψ is a function of ζ and φ and given in Figure 6, page 31.

$$\frac{(m'\, l)^2}{F_{st}^3}\ \frac{400}{\dfrac{1}{10\, S\, l} + \dfrac{100}{E\, A}} \qquad (20)$$

l = distance between supports, in metres
S = resulting spring constant of two conductor supports in newtons per millimetre
E = Young's modulus in newtons per square millimetre
A = conductor square section in square millimetres

For insulators, clamps, etc., of station components the value $S = 100$ N/mm may be used if no more accurate value is known.

7.2 *Tensile force F_f after the short-circuit (fall of span)*

This force is only considered when:

$$\frac{F'_o}{g_n\, m'} > 0.6 \tag{21}$$

In this case is to be applied:

$$F_f = F_{st60} \sqrt{1 + \frac{4\,F'_o}{g_n\, m'}\,\zeta} \qquad \text{if} \quad \frac{F'_o}{g_n\, m'} < 2 \tag{22}$$

$$F_f = F_{st60} \sqrt{1 + 8\zeta} \quad \text{if} \quad \frac{F'_o}{g_n\, m'} \geqslant 2 \tag{23}$$

where F_{st60} is the static tension in the conductor at a conductor-temperature of 60 °C.

Notes 1. — The resonance frequencies of these flexible conductors are low, and higher forces due to resonance are not expected.

2. — Due to conductor motion the stress may be lower than given by the formulae. The use of lower stress is acceptable when it can be demonstrated either by calculation or by tests.

3. — In the case of twin-conductors where the single conductors touch each other effectively the tension force F_t is higher than in formula (17).

8. Permitted load on post insulators and terminals

The dynamic force F_d for rigid conductors and F_t and F_f for flexible conductors, shall not be higher than the rated withstand value given by the support and insulator manufacturer. For an insulator stressed by a bending force the rated withstand value is given for a force acting on the insulator head. For a force acting at a point higher than the insulator head, a value lower than the rated withstand value which gives a moment the insulator can withstand, is to be used.

Connectors of rigid conductors shall be rated on the basis of F_d, while connectors for flexible conductors shall be rated on the basis of force peaks of 1.5 F_t or 1.0 F_f.

Note. — The factor 1.5 takes into account the effect of oscillations absorbed by the mass of the insulators.

SECTION TWO — THE THERMAL EFFECT ON BARE CONDUCTORS

9. General

This section gives calculation methods for the thermal effect on bare conductors. For cables and insulated conductors reference is given to the appropriate IEC Technical Committee and Sub-Committee*.

The heating of conductors due to short-circuit currents involves several phenomena of a non-linear character and other factors that have to be either neglected or approximated in order to make a mathematical approach possible.

For the purpose of this section the following assumptions have been made:

- Proximity-effect (magnetic influence of nearby parallel conductors) has been disregarded.

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* Technical Committee No. 20: Electric Cables. Sub-Committee 20A: High-voltage Cables.

- Resistance-temperature characteristic has been assumed linear.
- The specific heat of the conductor is considered constant.
- The heating is generally considered adiabatic.

10. Calculation of temperature rise

10.1 *General*

The loss of heat from a conductor during the short-circuit is very low, and the heating can generally be considered adiabatic. The calculation in this section is based on adiabatic conditions.

When repeated short-circuits occur with a short-time interval between them (i.e. rapid auto-reclosure) the cooling down in the short dead-time is of relatively low importance, and the heating can still be considered adiabatic. In cases where the dead-time interval is of longer duration (i.e. delayed auto-reclosure) the heat loss may be taken into account.

The calculation does not take into account the skin effect, i.e. the current is regarded as evenly distributed over the conductor cross-section area. This approximation is not valid for large cross-sections, and therefore for cross-sections above 600 mm^2 the skin effect shall be taken into account. For calculation, refer to the literature.

Note. — If the main conductor is composed of sub-conductors, uneven current distribution between the sub-conductors will influence the temperature rise of sub-conductors.

10.2 *Calculation of thermal equivalent short-circuit current*

The thermal equivalent short-circuit current is to be calculated using the short-circuit current r.m.s. value and the factors *m* and *n* for the time-dependent heat effects of the d.c. and a.c. components of the short-circuit current.

The thermal equivalent short-circuit current can be expressed by:

$$I_{th} = I_k'' \sqrt{m + n} \qquad (24)$$

where *m* and *n* are numerical factors, I_k'' the r.m.s. value of the initial symmetrical short-circuit current; in a three-phase system, the balanced three-phase short-circuit is decisive. The values *m* and *n* are shown in Figure 7, page 32, as functions of the duration of the short-circuit current. For a distribution network usually $n = 1$.

Note. — The relation I_k''/I_k is dependent on the impedance between the short-circuit and the source.

When a number of short-circuits occur with a short time interval in between, the resulting thermal equivalent short-circuit current is obtained from:

$$I_{th} = \sqrt{\frac{1}{T_k} \sum_{i=1}^{n} I_{thi}^2 \, T_{ki}} \qquad (25)$$

where:

$$T_k = \sum_{i=1}^{n} T_{ki} \qquad (26)$$

10.3 *Calculation of temperature rise and rated short-time current density for conductors*

The temperature rise in a conductor caused by a short-circuit is a function of the duration of the short-circuit current, the thermal equivalent short-circuit current and the conductor material.

By use of the graphs in Figure 8, page 33, it is possible to calculate the temperature rise of a conductor when the short-time current density is known or vice versa.

The highest recommended short-time temperature for different conductors is given in Table V.

Note. — The maximum permitted temperature of the support has to be taken into account.

10.4 *Calculation of the thermal short-circuit strength for different durations of the short-circuit current*

Electrical equipment has sufficient thermal short-circuit strength as long as the following relations hold for the thermal equivalent short-circuit current I_{th}:

$$I_{th} \leqslant I_{thr} \quad \text{for } T_k \leqslant T_{kr} \tag{27a}$$

or

$$I_{th} \leqslant I_{thr} \sqrt{\frac{T_{kr}}{T_k}} \quad \text{for } T_k \geqslant T_{kr} \tag{27b}$$

where I_{thr} is the rated short-time current and T_{kr} the rated short-time.

The thermal short-circuit strength for bare conductors is sufficient when the thermal equivalent short-circuit current density S_{th} satisfies the following relation:

$$S_{th} \leqslant S_{thr} \sqrt{\frac{T_{kr}}{T_k}} \tag{28}$$

with $T_{kr} = 1$ s and for all T_k.

The rated short-time current density S_{thr} is shown in Figure 8, page 33.

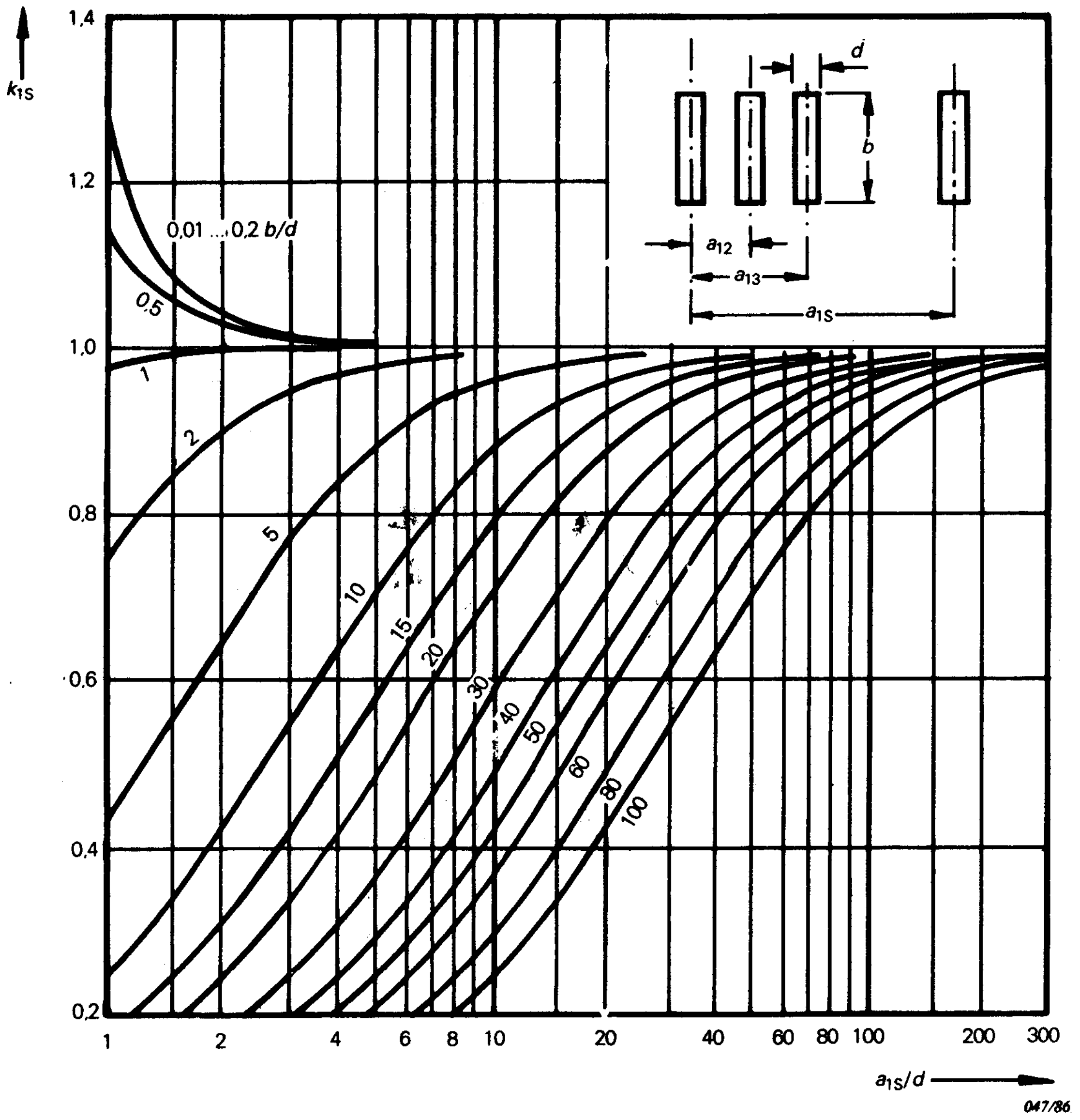


FIG. 1. — Factor k_{1s} for effective conductor central distance a_s.

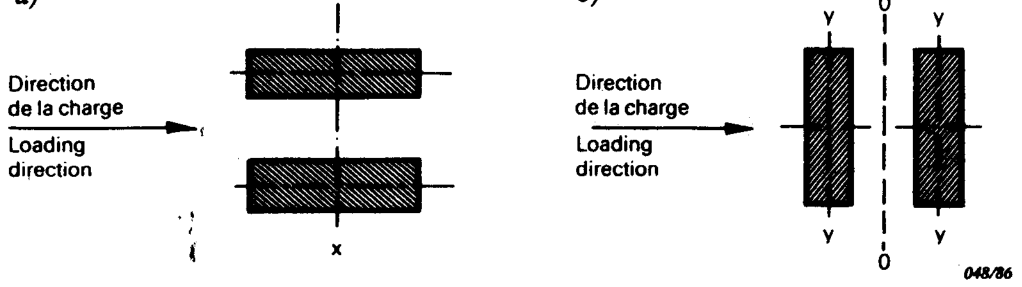


FIG. 2. — Loading direction and bending axis with multiple conductor arrangements.

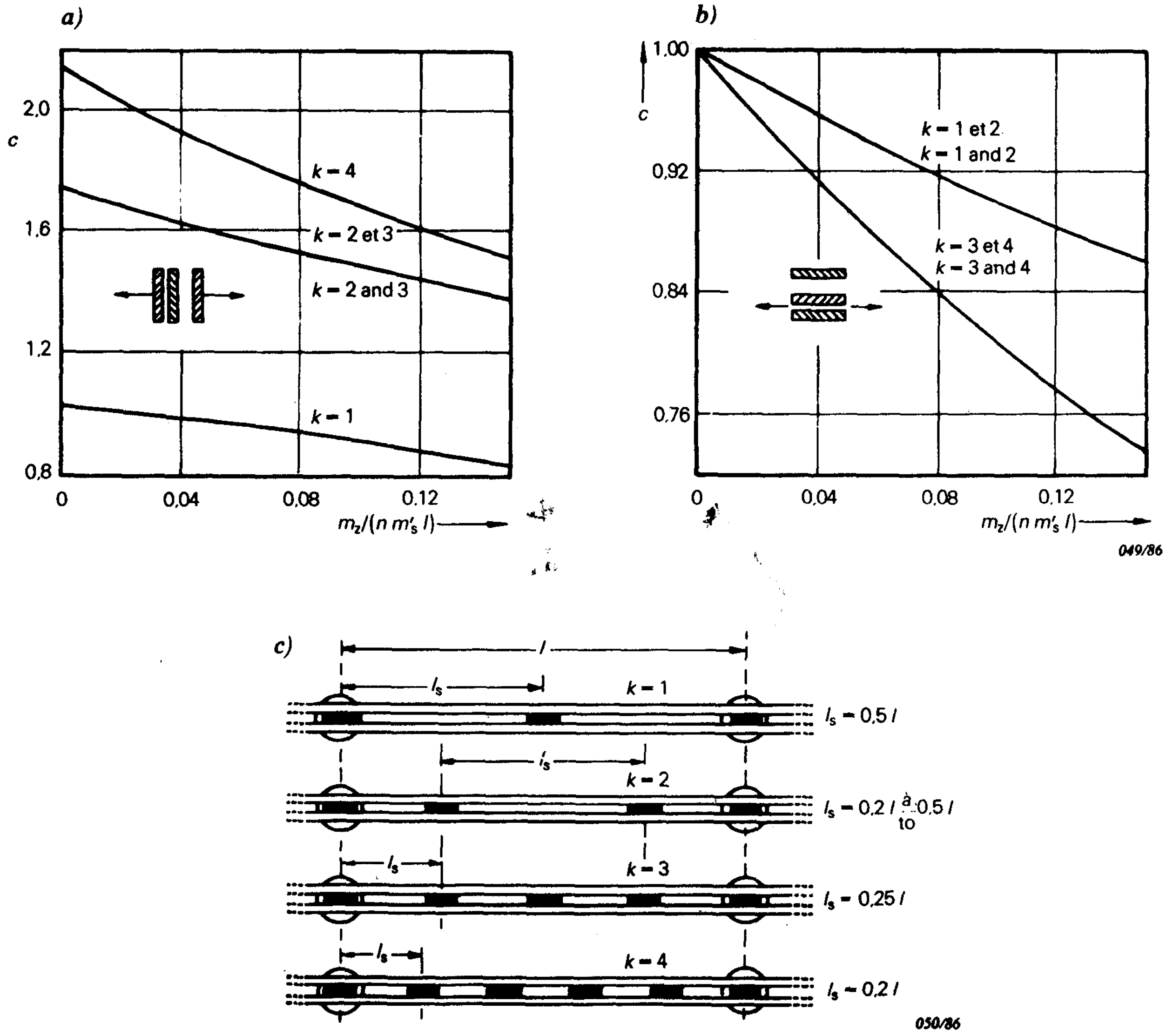


FIG. 3. — Factor *c* for the influence of spacers or stiffening elements in formula (15).

a) direction of oscillation vertical to the surface, with *k* number of stiffening elements;

b) vibration in any direction with *k* number of spacers or direction of vibration along the surface with *k* number of stiffening elements;

c) arrangement of stiffening elements or spacers.

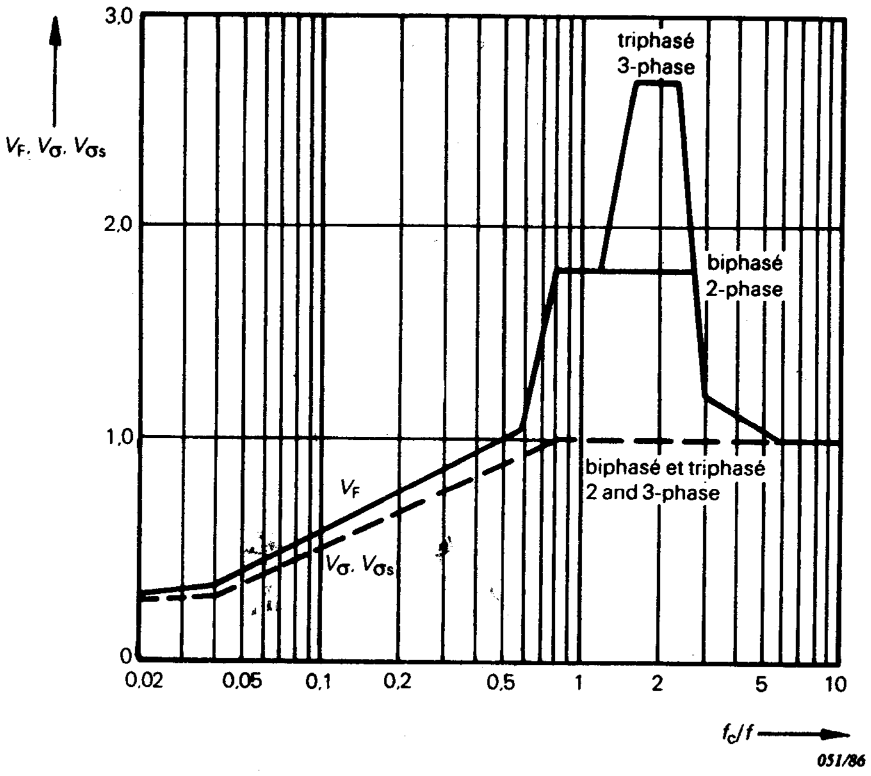


FIG. 4. — Factors V_F, V_σ and $V_{\sigma s}$ to be used with the two-phase and three-phase short-circuits; except arrangements with $f_c/f < 0.5$ in which $\kappa < 1.6$.

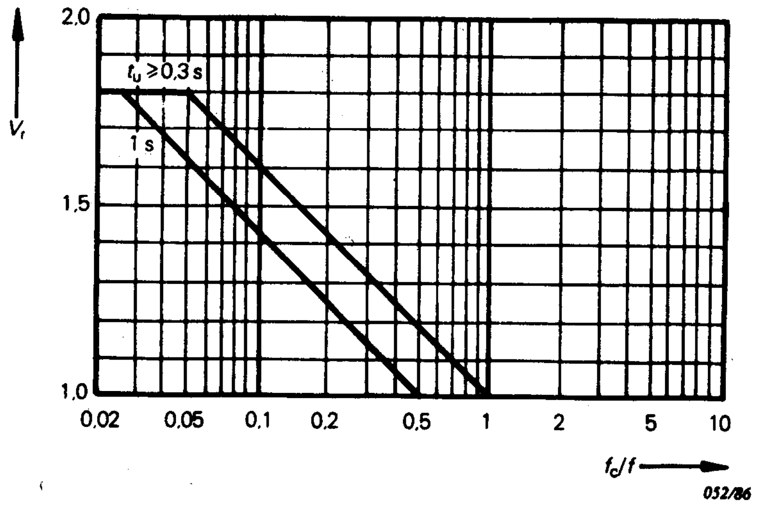


FIG. 5. — Factor V_r to be used with three-phase auto-reclosure.

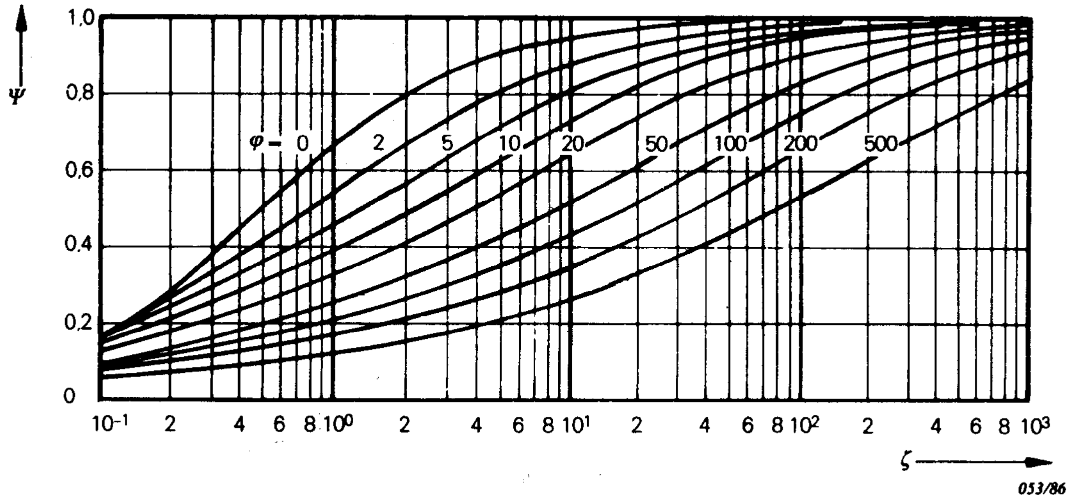


FIG. 6. — Factor ψ for tensile force in flexible conductors. The connection between the factors ψ, ζ and φ is given by:

$$\zeta = \frac{(1 + \varphi\psi)^2}{2 + \varphi + \varphi\psi} \cdot \frac{\psi}{1 - \psi}$$

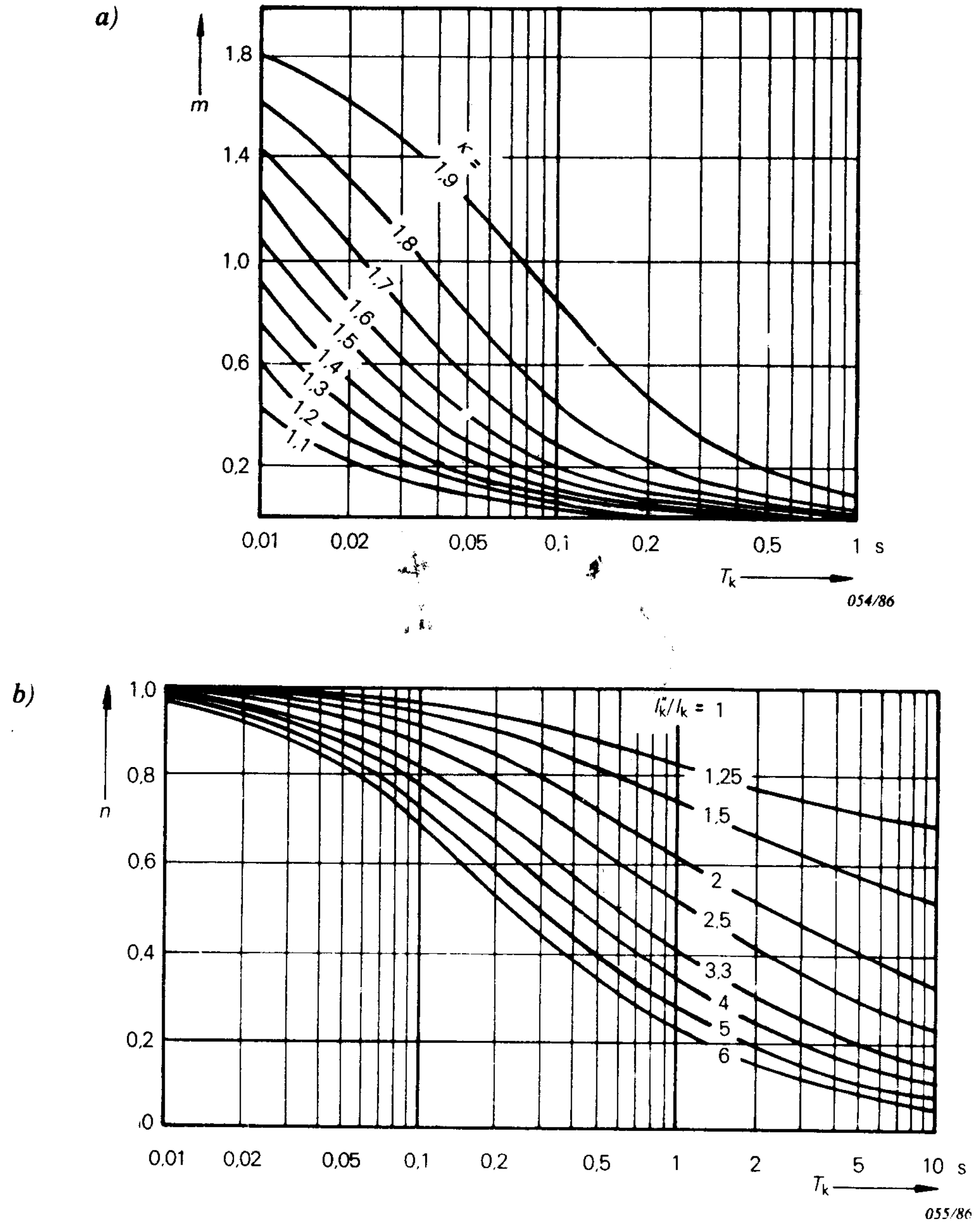


FIG. 7. — *a)* Factor *m*, heat dissipation due to d.c. component.
b) Factor *n*, heat dissipation due to a.c. component.

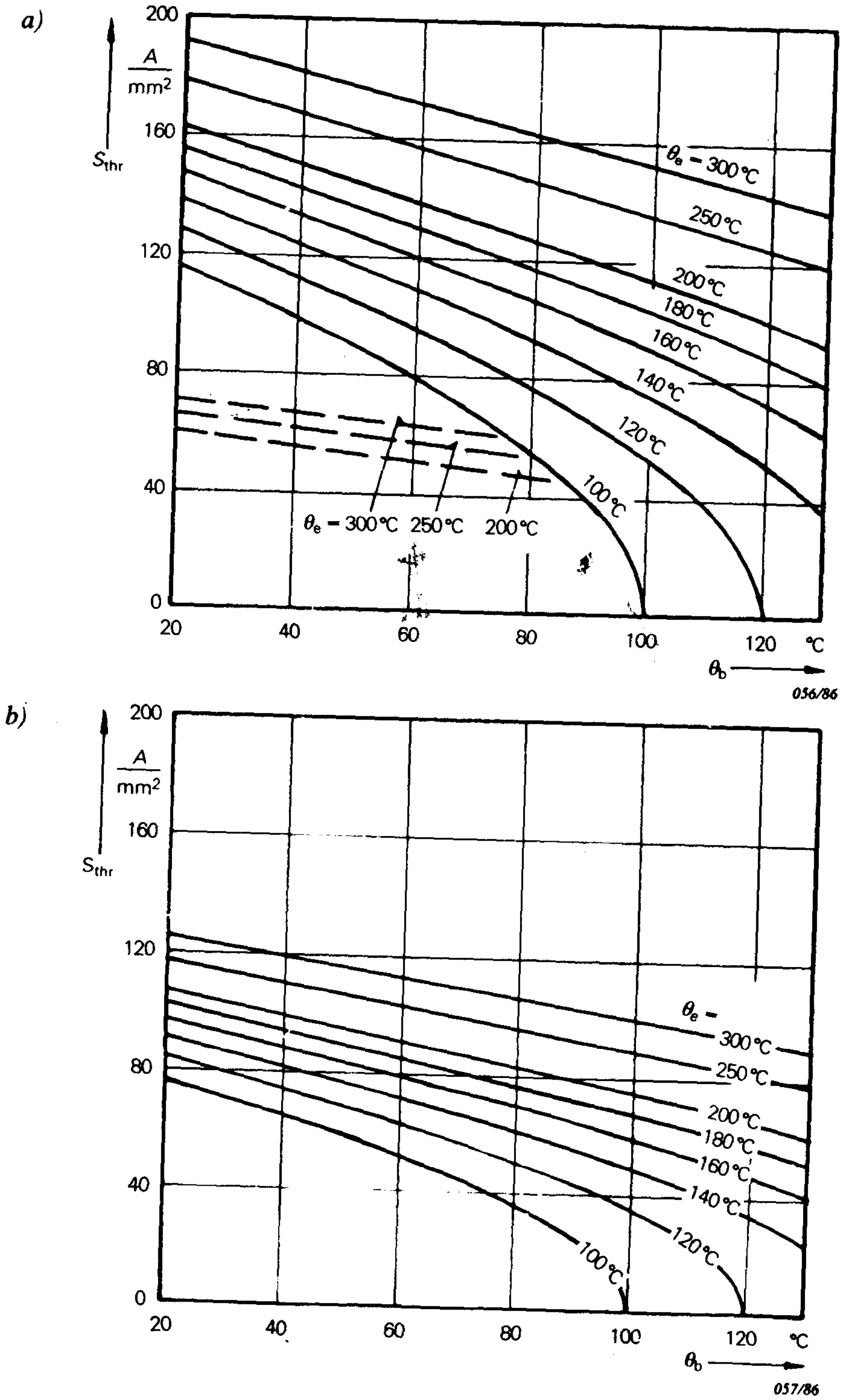


FIG. 8. — Relation between rated short-time current density (T_{kr} = 1 s) and conductor temperature.

a) Full lines: Copper
Dotted lines: Flat product of unalloyed steel and steel cables.
b) Aluminium, aluminium alloy, aluminium conductor steel reinforced (ACSR).

TABLE I

Effective conductor central distance a_s in metres, for rectangular section dimensions

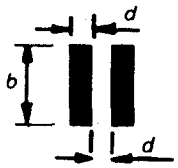
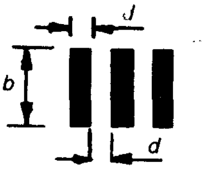
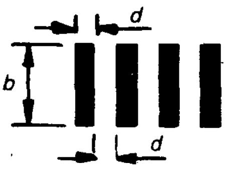
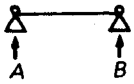
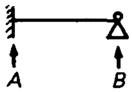
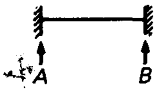
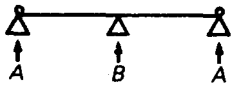
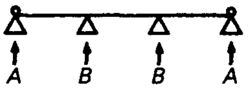
Rectangular sections	*b* *d*	0.04	0.05	0.06	0.08	0.10	0.12	0.16	0.20
	0.005 0.010	0.020 0.028	0.024 0.031	0.027 0.034	0.033 0.041	0.040 0.047	— 0.054	— 0.067	— 0.080
	0.005 0.010	— 0.017	0.013 0.019	0.015 0.020	0.018 0.023	0.022 0.027	— 0.030	— 0.037	— 0.043
	0.005 0.010	— 0.014	— 0.015	— 0.016	— 0.018	— 0.020	— 0.022	— 0.026	— 0.031

TABLE II

The factors α, β and γ for different support arrangements

Type of beam and supports		Factor α	Factor β	Factor γ
Single span beam	A and B simple supports 	A: 0.5 B: 0.5	1.0	0.157
	A: fixed support B: simple support 	A:0.625 B: 0.375	0.73	0.245
	A and B: fixed supports 	A:0.5 B: 0.5	0.5	0.356
Continuous beams with equidistant simple supports	Two spans 	A: 0.375 B: 1.25	0.73	0.245
	Three or more spans 	A: 0.4 B: 1.1	0.73	0.356

Notes 1. — Non-uniform span in continuous beams may be treated, with a sufficient degree of accuracy, as though the maximum span applied throughout. This means that:

- the end supports are not subjected to greater stress than the inner ones;
- spans should not differ in length from adjacent ones by more than 20%. If that does not prove to be possible, the conductors can be decoupled using flexible joints;

2. — The β-values are so calculated that a permissible plastic deformation occurs. They are so chosen that the same *q*-value (see Sub-clause 6.2.1 and Table III) can be used for all conductor-support arrangements.

TABLE III

Acceptable q-values for different cross-sections

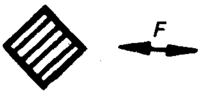
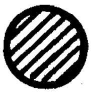
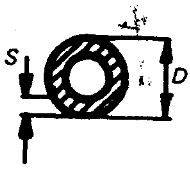
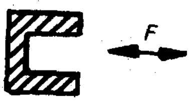
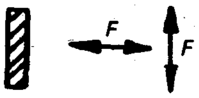
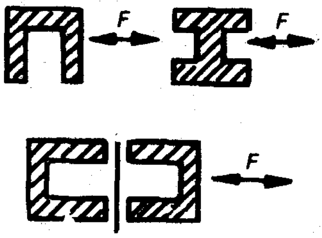
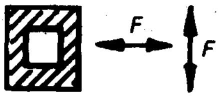
Cross-sections	q
	2.00
	1.70
	$\left(\frac{S}{D} = 0.05\right)$, 1.34 (= 0.075), 1.37 (= 0.100), 1.40 (= 0.125), 1.44 (= 0.160), 1.48 (= 0.200), 1.51
	1.83
	1.50
	1.19
	1.13

TABLE IV

Section moduli Z in cubic centimetres of main conductors with two and more stiffening elements

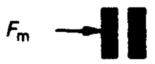
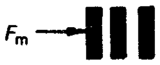
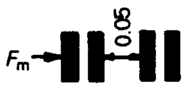
Geometrical configuration	m × m							
	0.04×0.01	0.05×0.01	0.06×0.01	0.08×0.01	0.10×0.01	0.12×0.01	0.16×0.01	0.20×0.01
	3.5	4.3	5.2	6.9	8.7	10.4	13.9	17.4
	7.9	9.9	11.9	15.8	19.8	23.8	31.7	39.6
	6.9	8.7	10.4	13.9	17.3	20.8	27.7	34.7

TABLE V

Recommended highest conductor temperatures in the case of short circuit

Type of conductors	Max. recommended conductor temperature in case of short-circuit
Mechanical loaded bare conductors, solid or stranded, Al or Cu	200°C
Aluminium alloy	170°C
Loaded steel	250°C
Unloaded steel	300°C
Cables and conductors, paper and plastics insulated	*

* Recommended temperatures are dealt with by IEC Technical Committee No. 20: Electric Cables, and Sub-Committee 20A: High-voltage Cables.

APPENDIX

EXAMPLES OF CALCULATION OF THE EFFECTS OF SHORT-CIRCUIT CURRENTS

Example 1. Mechanical effects on single rigid conductors

Basis for the calculations in this example is a three-phase system with one bus-bar per phase. The bus-bars are mounted on edge. The cross-section is 60 × 10 mm² and the material is an Al-Mg-Si-alloy.

The following data are given:

$l = 1.0\ \text{m}$ $\quad E = 70\,000\ \text{N/mm}^2$
$a = 0.2\ \text{m}$ $\quad J = 0.5\ \text{cm}^4$
$i_{p3} = 30\ \text{kA}$ $\quad Z = 1.0\ \text{cm}^3$
$m' = 1.62\ \text{kg/m}$ $\quad R_{p0.2} = 120\ \text{N/mm}^2$ up to $180\ \text{N/mm}^2$

Number of spans: 3

The natural frequency of the bus-bars is:

$$f_c = \frac{\gamma}{l^2}\sqrt{\frac{EJ}{m'}} = \frac{0.356}{1.0^2}\sqrt{\frac{70\,000 \cdot 0.5}{1.62}} = 52.3\ \text{Hz}$$

The ratio $\frac{f_c}{f}$ is 1.05. This gives the following values to the factors V_F, V_σ and V_r:

$V_F = 1.8 \quad \text{if } V_F \cdot V_r < \frac{0.8\, R_{p0.2}}{\sigma_m}$ (with the upper value of $R_{p0.2}$)

$V_\sigma = 1.0$

$V_r = 1.0$

Maximum force on the central bus-bar is:

$$F_m = 0.2 \cdot 0.87 \cdot i_{p3}^2 \cdot \frac{l}{a} = 0.2 \cdot 0.87 \cdot 30^2 \cdot \frac{1.0}{0.2} = 783\ \text{N}$$

Maximum bending stress is:

$$\sigma_m = V_\sigma V_r \beta \frac{F_m l}{8Z} = 1.0 \cdot 1.0 \cdot 0.73\ \frac{783 \cdot 1.0}{8 \cdot 1.0} = 71.5\ \text{N/mm}^2$$

Maximum bending force on the supports is:

$$F_d = V_F V_r \alpha F_m = 1.8 \cdot 1.0 \cdot 1.1 \cdot 783 = 1\,550\ \text{N}$$

The bus-bars are assumed to withstand the short-circuit force if:

$\sigma_m < q\, R_{p0.2}$ (with the lower value of $R_{p0.2}$)

For a rectangular cross-section $q = 1.5$. This gives:

$$\sigma_m < 1.5 \cdot 120 = 180\ \text{N/mm}^2$$

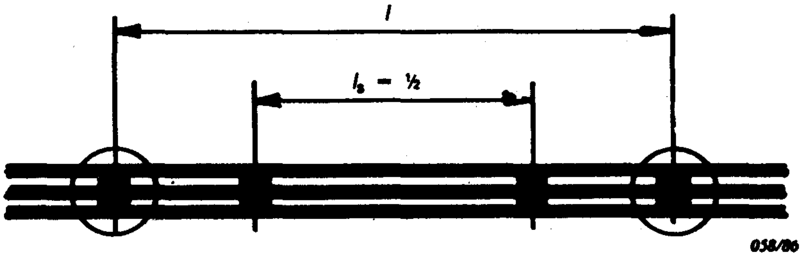
Conclusions:

The bus-bars will withstand the short-circuit force.

The supports have to withstand a dynamic bending force of 1 550 N.

Example 2. **Mechanical effects on multiple rigid conductors**

Basis for the calculations in this example is the same three-phase system as in example 1, with three bus-bars per phase. Between two supports there are two spacers. The spacers are 0.06 m × 0.06 m. The cross-sections of the individual bus-bars are 60 × 10 mm². The distance between the individual bus-bars is 10 mm. The other data are the same as in example 1.



Position of the spacers

The natural frequency of the main bus-bar is:

$$f_c = c f_0 = 0.96 \cdot 52.3 = 50.2 \text{ Hz}$$

When c is taken from Figure 3*b)*, page 29, with $k = 2$ as a function of the ratio:

$$\frac{m_z}{n\, m'_s\, l} = \frac{1.6 \cdot 0.06 \cdot 2}{3 \cdot 1.6 \cdot 1.0} = 0.04$$

This gives $c = 0.96$.

The natural frequency of the individual bus-bars is:

$$f_s = \frac{\gamma}{l_s^2} \sqrt{\frac{E J_s}{m'_s}} = \frac{0.356}{0.5^2} \sqrt{\frac{70\,000 \cdot 0.5}{1.62}} = 209.3 \text{ Hz}$$

The ratio $\frac{f_c}{f}$ and $\frac{f_s}{f}$ gives the following values to the factors V_F, V_σ, $V_{\sigma s}$ and V_r:

$V_F = 1.8$ if $V_F \cdot V_r < \frac{0.8 \cdot R_{p0.2}}{\sigma_{tot}}$ (with the upper value of $R_{p0.2}$)

$V_\sigma = 1.0$

$V_{\sigma s} = 1.0$

$V_r = 1.0$

Maximum bending stress in the main bus-bar corresponding to one phase is:

$$\sigma_m = V_\sigma V_r \beta \frac{F_m l}{8 Z} = 1.0 \cdot 1.0 \cdot 0.73 \cdot \frac{783 \cdot 1.0}{8 \cdot 3.0} = 23.8 \text{ N/mm}^2$$

When Z is found from Figure 2*b)*, page 28.

$$Z = 3 \text{ cm}^3$$

Maximum force between individual bus-bars is:

$$F_s = 0.2 \left(\frac{i_{p3}}{n}\right)^2 \frac{l_s}{a_s} = 0.2 \cdot 10^2 \frac{0.5}{0.02} = 500 \text{ N}$$

Maximum bending stress in the individual bus-bars is:

$$\sigma_s = V_{\sigma s} V_r \frac{F_s l_s}{16 Z_s} = 1.0 \cdot 1.0 \frac{500 \cdot 0.5}{16 \cdot 1.0} = 15.6 \text{ N/mm}^2$$

Total bending stress in the bus-bar material is:

$$\sigma_{tot} = \sigma_m + \sigma_s = 23.8\ \text{N/mm}^2 + 15.6\ \text{N/mm}^2 = 39.4\ \text{N/mm}^2$$

Maximum bending force on the supports is:

$$F_d = V_F\, V_r\, \alpha\, F_m = 1.8 \cdot 1.0 \cdot 1.1 \cdot 783 = 1\,550\ \text{N}$$

The bus-bar is assumed to withstand the short-circuit force if:

$$\left.\begin{array}{l} \sigma_{tot} = 39.4\ \text{N/mm}^2 < 1.5 \cdot 120\ \text{N/mm}^2 \\ \sigma_s\ \ = 15.6\ \text{N/mm}^2 < 120\ \text{N/mm}^2 \end{array}\right\} \text{(with the lower value of } R_{p0.2}\text{)}$$

Conclusions:

The bus-bar will withstand the short-circuit force.

The supports have to withstand a bending force of 1 550 N.

Example 3. Mechanical effects on slack conductors

Basis for the calculations in this example is a three-phase flexible bus-bar connection with one all-aluminium stranded conductor of $A = 240\ \text{mm}^2$ per phase. The span length is $l = 11.5$ m. The anchor points at each end of the span are post insulators on steel substructures with a resultant spring constant of $S = 100$ N/mm. Therefore the static tensions of the conductors $F_{st} = 400$ N may be considered nearly invariable within a temperature range of −20 °C to 60 °C.

The following data are given additionally and necessarily:

$I_{k3} = 15$ kA $\quad E = 60\,000\ \text{N/mm}^2 \quad g_n = 9.81\ \text{m/s}^2$

$a = 1.25$ m $\quad m' = 0.67$ kg/m

The force F'_0 is:

$$F'_0 = 0.15\ \frac{I_{k3}^2}{a} = 0.15\ \frac{15^2}{1.25} = 27\ \text{N/m}$$

The factor φ is:

$$\varphi = 3\left[\sqrt{1 + \left(\frac{F'_0}{g_n\, m'}\right)^2} - 1\right] = 3\left[\sqrt{1 + \left(\frac{27}{9.81 \cdot 0.67}\right)^2} - 1\right] = 9.68$$

The factor ζ is:

$$\zeta = \frac{(m'\, l)^2}{F_{st}^3}\ \frac{400}{\dfrac{1}{10\, S\, l} + \dfrac{100}{E\, A}} = \frac{(0.67 \cdot 11.5)^2}{400^3}\ \frac{400}{\dfrac{1}{10 \cdot 100 \cdot 11.5} + \dfrac{100}{60\,000 \cdot 240}} = 3.95$$

For $\zeta = 3.95$ and $\varphi = 9.68$ Figure 6, page 31, shows $\psi = 0.59$.

The tension in the conductor during the short-circuit is given by:

$$F_t = F_{st}\,(1 + \varphi\, \psi) = 400\,(1 + 9.68 \cdot 0.59) = 2\,684\ \text{N}$$

Because:

$$\frac{F'_0}{g_n m'} = \frac{27}{9.81 \cdot 0.67} = 4.11 > 2$$

a tensile force F_f after the short-circuit can occur which is given by:

$$F_f = F_{st}\,\sqrt{1 + 8\,\zeta} = 400\,\sqrt{1 + 8 \cdot 3.95} = 2\,284\ \text{N}$$

Conclusions:

The supports (post insulators and steel substructure) have to withstand a dynamic bending force of 2 684 N, given by the conductor tension during the short circuit.

The clamping device for the conductor anchoring shall be rated on a basis of force peaks of $1.5 \cdot 2\,684 = 4\,026$ N.

Example 4. Thermal effects on bare conductors

Basis for the calculation is the same three-phase system as in example 1.

Following data are given:

$$I_k'' = 17\,\text{kA} \qquad I_k = 17\,\text{kA} \qquad i_{p3} = 30\,\text{kA}$$
$$\kappa = 1.25 \qquad T_k = 2.0\,\text{s}$$

When $\theta_b = 65\,°\text{C}$ and $\theta_e = 170\,°\text{C}$, S_{thr} is found from Figure 8*b)*, page 33.

$$S_{thr} = 80\,\text{A/mm}^2$$

This gives:

$$I_{thr} = S_{thr} \cdot A = 80\,\text{A/mm}^2 \cdot 60\,\text{mm} \cdot 10\,\text{mm} = 48\,\text{kA}$$

$$I_{th} = I_k'' \sqrt{m+n} = 17\sqrt{0+1} = 17\,\text{kA}$$

m and n are found from Figures 7*a)* and 7*b)*, page 32. The bus-bars have sufficient thermal strength when:

$$I_{th} < I_{thr}\sqrt{\frac{T_{kr}}{T_k}} = 48\sqrt{\frac{1}{2}} = 33.9\,\text{kA}$$

Conclusion:

The bus-bars have sufficient thermal strength.

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